

Search for the Cosmic Neutrino Background and KATRIN.

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Devoted to the 70th. birthday of Apolodor Raduta.

Abstract.

The Cosmic Microwave Background (CMB) has been detected in 1964 by Penzias and Wilson. It shows today a remarkable constant temperature of $T_{0\gamma} \approx 2.7$ K independent of the direction. Present density is about 370 photons per cm^3 . The size of the hot spots, which deviates only in the fifth decimal of the temperature from the average value, tells us, that the universe is flat. About 300 000 years after the Big Bang at a temperature of $T_{0\gamma} = 3000$ K already in the matter dominated era the electrons combine with the protons and the ${}^4\text{He}$ and the photons move freely in the neutral universe. So the temperature and distribution of the photons give us information of the universe 300 000 years after the Big Bang. Information about earlier times can, in principle, be derived from the Cosmic Neutrino Background ($C\nu B$). The neutrinos decouple already 1 second after the Big Bang at a temperature of about 10^{10} K. Today their temperature is ~ 1.95 K and the average density is 56 electron-neutrinos per cm^3 . Registration of these neutrinos is an extremely challenging experimental problem which can hardly be solved with the present technologies. On the other hand it represents a tempting opportunity to check one of the key element of the Big Bang cosmology and to probe the early stages of the universe evolution. The search for the $C\nu B$ with the induced beta decay $\nu_e + {}^3\text{H} \rightarrow {}^3\text{He} + e^-$ is the topic of this contribution. The signal would show up by a peak in the electron spectrum with an energy of the neutrino mass above the Q value. We discuss the prospects of this approach and argue that it is able to set limits on the $C\nu B$ density in our vicinity.

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1. Introduction

The Cosmic Microwave Background (CMB) was detected in 1964 by Penzias and Wilson [1] (Nobel Prize 1978) as byproduct of their search for possible perturbations of the communication with satellites. It supported the Big Bang (BB) model for the early universe. The temperature followed exactly Planck's distribution and was surprisingly identical to four digits independent of the direction ($T_{0\gamma} = 2.7255(6)$ Kelvin). This led to the 'inflationary' model. The satellite observations COBE (Cosmic Background Explorer) [2] in 1990, WMAP (Wilkinson Microwave Anisotropy Probe) [3] 2001 and Planck [4] in 2013 did show deviations of the constant temperature of the background photons in the fifth digit. The size of these 'hot spots' indicated a flat universe. These measurements show a picture of our universe at the decoupling of the photons from matter and give us information of the universe about 300 000 years after the big bang (BB) at a temperature of about 3000 Kelvin and the scale of the expanding universe roughly 1/1000 of today. The radius of this sphere of the last interaction is from each observer in the universe about 13 to 14 billion light years (ly) away, reflecting the age of the universe.

Therefore with photons we are unable to probe the universe closer than 300 000 years to the BB. The relative abundance of light nuclear isotopes allows indirectly to look to events minutes after the BB. A similar probe like the photons are the neutrinos. Due to their weak interaction they decouple earlier about 1 second after the BB from matter at a temperature of $T_{0\nu} \approx 1\text{MeV} \approx 10^{10}$ Kelvin. The Cosmic Neutrino Background ($C\nu B$) of today $T_{0\nu} \approx 1.95$ K contains therefore information of the universe already ~ 1 second after the BB. The detection of this $C\nu B$ seems to be hardly possible due to the weak interaction of neutrinos with matter and due to their low energy ($T_{\nu} = 1.95$ K $\approx 2 \cdot 10^{-4}$ [eV]). Nevertheless several methods have been discussed in the literature to search for these relic neutrinos [5, 6, 7, 8, 9, 10, 11, 12, 13]. Let us mention among them the following proposals:

- Annihilation of an ultrahigh energy cosmic neutrino with a relic antineutrino into the Z-resonance [13]. Energy and momentum conservation require, that the Z-boson has an energy of $E_Z = 4 \cdot 10^{22}$ [eV]. If the decay Z-burst is directed to the earth one should observe several gamma rays, nucleons or electrons above the Greisen-Zatsekin-Kuzmin cutoff of about 10^{21} [eV], if the event is within the GZK-radius off about 50Mpc .
- Like in the case of dark matter the solar system with the earth is probably moving with some speed through the relic neutrino cloud [14]. One fixes a cylindrical object free in space frictionless with magnetic forces. Divided by a plane going through the cylindrical symmetry axis half the material can absorb relic neutrinos like ^{187}Re and the other half has the same weight, but cannot absorb relic neutrinos. The 'neutrino wind' exerts a torque to this cylindrical object and turns it so into the 'neutrino wind', so that the torque is zero.
- The search for the $C\nu B$ with the induced beta decay [5, 6].

$$\nu_e + {}^3\text{H} \rightarrow {}^3\text{He} + e^- . \quad (1)$$

The signal would show up by a peak in the electron spectrum with an energy of the neutrino mass above the Q value. This reaction has no threshold and therefore should take place in the environment of the low energy $C\nu B$.

In the present contribution we focus on the last approach based on the $C\nu B$ with the induced beta decay. For the estimate average relic neutrino density of 56 neutrinos per cm^3 observation of this process with the existing technologies is not realistic. The chances may be improved for the smaller mass of the relic electron neutrinos, with the increase of the relic

neutrino density due to gravitational clustering and by the strength of the beta decay source (specifically the intensity of the tritium source). Despite of this pessimistic situation with the detection of $C\nu B$, from the searches of the reaction (1) at least it should be possible to derive an upper limit for the overdensity of the relic neutrinos in our galaxy due to gravitational clustering. We shell comment this point in the present note.

In sec. 2 and 3 we briefly give a cosmological background relevant for the subject in question with motivations of searching for $C\nu B$. In sec. 4 we present a formalism for analysis of both the relic neutrino capture reaction (1) and tritium beta decay. Then we discuss prospects of searches for the reaction (1) with KATRIN experiment [18].

2. Cosmology of the Microwave Background

The detection and measurement of the Cosmic Background Radiation in 1964 by Penzias and Wilson [1] surprised, because the radiation followed very accurately Planck's black body radiation law:

$$\epsilon(f)df = \frac{8\pi h}{c^3} \cdot \frac{f^3 df}{\exp(hf/k_B T_0) - 1} [Energy/Volume] \quad (2)$$

The temperature parameter T_0 fitted by (2) is independent of the observation direction up to the fourth digit. The average temperature of the photons in the CMB is about $3 \cdot T_0$.

$$T_{0,rad} \equiv T_{0,\gamma} = 2.7255 \pm 0.0006 [Kelvin] \quad (3)$$

Integration over all frequencies f yields the Stefan-Boltzmann law for the energy density.

$$\epsilon_{rad} = \varrho_{rad} c^2 = \alpha T_0^4; \quad \alpha = \frac{\pi^2 k_B^4}{16 \hbar^3 c^3}; \quad (4)$$

With:

$$k_B \approx 0.86 \cdot 10^{-4} [eV/Kelvin]; \quad 1[eV] \approx 11600 [Kelvin]; \quad (5)$$

The average number of photons can be calculated by dividing (4) by the energy $3 \cdot k_B T_0$ of the average photons in the CMB.

$$n_\gamma \approx 370 \text{ cm}^{-3} \quad (6)$$

The size of the 'hot spots' above the average temperature of the CMB with $T_{0,\gamma} = 2.7255[Kelvin]$ indicates a flat universe with the critical density:

$$\varrho_c = \frac{3H^2}{8\pi G} = 0.94 \cdot 10^{-26} [kg \cdot m^{-3}]; \quad G_{gravitation} = 6.67 \cdot 10^{-11} [m^3 kg^{-1} sec^{-2}]; \quad (7)$$

The baryon density in the universe can be extracted from the relative abundance of the light nuclear isotopes, including the 25 % mass fraction of 4He . This yields a baryon density in units of the critical density (7) of:

$$\Omega_{baryon} = \frac{\varrho_{baryon}}{\varrho_c} = 0.04; \quad (8)$$

The photon energy density in the same units is:

$$\Omega_{rad} = \frac{\varrho_{rad}}{\varrho_c} = 4.90 \cdot 10^{-5}; \quad (9)$$

Although the energy density of the photons (rad) is much smaller than the one of the baryons, the number density of the photons is nine orders larger than the one of the baryons.

$$\frac{n_\gamma}{n_{baryon}} \approx 1.7 \cdot 10^9; \quad (10)$$

The photons decouple from matter as soon as the electrons get bound to the protons and to the ${}^4\text{He}$ nuclei and the universe is electrically neutral. This does not happen after the temperature of the universe goes below the ionisation energy of hydrogen of 10 to 13 [eV]. Due to the nine orders of photons more than baryons it is enough, if one photon of the about 10^9 per baryon at the high energy end of the Planck distribution (2) ionizes the hydrogen atoms. So the decoupling of the CMB happens at the lower temperature of about 3000 Kelvin $\approx 0.3\text{ eV}$ roughly 300 000 years after the big bang. So since about 13 billion years the CMB move freely. The sphere of the last photon scattering has a radius of 13 to 14 billion light years around the observer.

3. Cosmology of the Cosmic Neutrino Background

The neutrinos are fermions and thus the Planck distribution (2) is modified accordingly.

$$\epsilon(f)df \propto \frac{f^3 df}{\exp(hf/k_B T_0) + 1} [\text{Energy/Volume}] \quad (11)$$

Again f is the frequency and h Planck's Wirkungsquantum.

The integration over the frequencies yields the total energy density of the neutrinos. Division by the average energy of relic neutrinos $3 \cdot k_B T_0 = 3 \cdot k_B \cdot (T_0 = 1.95 \text{ Kelvin (today)})$ yields the average number density for electron-neutrinos.

$$n(\text{today})_{\nu,e} = \frac{\epsilon(\text{today})_{\nu,e}}{3 \cdot k_B \cdot (T_0 = 1.95 \text{ Kelvin})} = 56 \text{ cm}^{-3} \quad (12)$$

For the total neutrino density this number has to be multiplied by 6.

The neutrinos decouple much earlier from matter than the photons due to their very weak interaction. The competition for decoupling of the neutrinos is between the expansion rate of the universe given by the Hubble constant

$$H = \frac{\dot{a}}{a} = \sqrt{\frac{8\pi G}{3} \varrho_{total}} = \sqrt{\frac{8\pi \varrho}{3M_{Planck}^2}} \propto a^{-4}; \quad (13)$$

and the reaction rate for relativistic neutrinos:

$$\Gamma = n_\nu \langle \sigma v \rangle \approx T_0^3 G_{Fermi} T_0^2 = G_F T_0^5 \propto a^{-5}; \quad v \approx c = 1. \quad (14)$$

The above equations are given in the natural units $\hbar = c = 1$ and $a \propto 1/T$ is the scale parameter of the universe. For decreasing temperature T and increasing scale $a = 1/T$ the Hubble expansion wins over the neutrino reaction rate and the neutrinos decouple, when the Hubble expansion rate (13) is about equal to the neutrino reaction rate (14):

$$\Gamma/H = (k_B T_0 / 1 \text{ MeV})^3 \approx 1; \quad T_0 = 1 \text{ MeV} \approx 10^{10} [\text{Kelvin}]; \quad (15)$$

in radiation dominated era: $T_0 = \left(\frac{45 \hbar^3 c^5}{32 \pi^3 G} \right)^{1/4} \cdot \frac{1}{t^{1/2}} \equiv 1.3 \left(\frac{t}{\text{sec}} \right)^{-1/2} [\text{MeV}];$

This corresponds to the time passed after the Big Bang about 1 second.

To find the temperature of the neutrino background today one has to take into account, that the photon background is heated up by the positron-electron annihilation into two photons after the decoupling of the neutrinos. This annihilation happened with constant entropy.

$$e^- + e^+ \rightarrow \gamma + \gamma; \quad S \propto g_i \cdot T_{0i}^3 = g_f \cdot T_{0f}^3 = \text{const}; \quad (16)$$

Constant entropy means equal degrees of freedom. The initial state of this phase transition are the electrons ($g_{e^-} = 2 \cdot 7/8$), positrons ($g_{e^+} = 2 \cdot 7/8$) and photons ($g_\gamma = 2$). While in the final state one has the photons only ($g_\gamma = 2$). The factor 7/8 takes into account the Pauli principle for the electrons. The temperature dependence $T_{i/f}^3$ is proportional to the degrees of freedom in momentum space.

$$g_i = 4 \cdot \frac{7}{8} + 2 = \frac{11}{2}; \quad g_f = 2; \quad \frac{g_f}{g_i} = \frac{4}{11} = \left(\frac{T_{0,i=\nu}}{T_{0,f=\gamma} = 2.725} \right)^3; \quad (17)$$

$$T_{0,\nu}(\text{today}) = 1.95 [\text{Kelvin}];$$

The relativistic massless neutrino energy density in relation to the critical density is now expressed by the photon background (9) given by:

$$\Omega_\nu = 3 \cdot \frac{7}{8} \cdot \left(\frac{4}{11} \right)^{4/3} \cdot \Omega_{rad} = 0.68 \cdot \Omega_{rad}; \quad (18)$$

The factor 3 originates from six different types of neutrinos and two photon degrees of freedom (6/2). Today the neutrinos are non-relativistic due to their finite mass and the low kinetic energy of about $3 \cdot T_0 = 3 \cdot 1.95 [\text{Kelvin}] \equiv 5.5 \cdot 10^{-4} [\text{eV}]$. For massive neutrinos the energy density in units of the critical density is:

$$\Omega(m_\nu \neq 0)_\nu = \Omega(m_\nu = 0) \cdot \frac{\sum m_\nu c^2}{3 \cdot k_B T} = \frac{\sum m_\nu c^2}{45 \text{ eV}}; \quad (19)$$

In summary the cosmological development starts with the radiation dominated era from the Big Bang (BB) till about 30 000 years after the BB with a temperature of $1 \text{ eV} \equiv 10\,000 \text{ Kelvin}$ at that time. In this era the neutrinos decouple at about 1 second after the BB and $T \approx 10^{10} \text{ Kelvin}$. The energy density scales with $a^{-4} \propto T^4$. The matter dominated era lasts from about 30 000 to $8 \cdot 10^9$ years after BB. In this era the photon background decouples at around 3000 Kelvin and 300 000 years after the BB. The energy scales during this time with $a^{-3} \propto T^3$. At around $8 \cdot 10^9$ years after BB the dark energy takes over with a constant energy density, which accelerates the expansion.

4. Search for the Cosmic Neutrino Background with KATRIN.

Here we discuss the relic neutrino induced beta capture (1) and the beta decay of tritium

$${}^3H \rightarrow {}^3He + e^- + \bar{\nu}_e; \quad Q = 18.562 \text{ keV} \quad (20)$$

with the focus on the KATRIN experiment [18] which we believe has the detection potential to set an upper limit for the relic electron neutrino density in our neighborhood.

The electron spectrum of the reactions (1) and (20) for tritium has for infinite good energy resolution the form:

$$\begin{aligned} \frac{dN_e}{dE} = & K \cdot F(E; Z) \cdot p_e E_e (E_0 - E_e) \sum_{j=1}^3 |U_{ej}|^2 \sqrt{(E_0 - E_e)^2 - m(\nu_j)^2} \\ & + \eta \cdot n_{\nu,e} \cdot \delta\left(E - Q - \sqrt{\sum_{j=1}^3 |U_{ej}|^2 m(\nu_j)^2}\right); \end{aligned} \quad (21)$$

with:

$$E_0 = Q + m_e; \quad Q = 18.562 \text{ keV}; \quad E_e = \sqrt{m_e^2 + p_e^2}; \quad E = T_e = E_e - m_e; \quad (22)$$

and the flavor state ν_e expressed by mass eigenstates ν_j :

$$\nu_e = \sum_{j=1,2,3} U_{ej} \nu_j; \quad m_{\nu,e}^2 = \sum_{j=1,2,3} |U_{ej}|^2 m_{\nu,j}^2; \quad (23)$$

To determine the neutrino mass one must fit the electron spectrum at the upper end of the Kurie plot of the tritium decay (20) the Q value with an accuracy of the order of milli-volt (mV) and the electron neutrino mass (23). To determine the local relic neutrino density or an upper limit for it, one has in addition to fit $\eta \cdot n_{\nu,e}$ from eq. (21), which is proportional to the local relic electron-neutrino density $n_{\nu,e}$ (see below).

The tritium beta decay probability is according to Fermi's Golden Rule given by:

$$\Gamma_{decay}^\beta({}^3H) = \frac{1}{2\pi^3} \cdot \sum \int | \langle {}^3He | T | {}^3H \rangle |^2 \cdot 2\pi \delta(E_\nu + E_e + E_f - E_i) \frac{d\vec{p}_e}{2\pi^3} \cdot \frac{d\vec{p}_\nu}{2\pi^3}; \quad (24)$$

One averages over the initial and sums over the final magnetic substates and integrates over the electron and neutrino momenta. The Beta decay matrix element contains Fermi and Gamow-Teller contributions.

$$\begin{aligned} \sum | \langle {}^3He | T | {}^3H \rangle |^2 &= 2 \cdot \left(\frac{G_F \cos(\vartheta_C)}{\sqrt{2}} \right)^2 \cdot F_0(Z+1, T_e) [B_F({}^3H) + B_{GT}({}^3H)]; \\ B_F({}^3H) &= |M_{Fermi}|^2 = \frac{1}{2} | \langle He(1/2)^+ | \sum_n \tau_n^+ | {}^3H(1/2)^+ \rangle |^2; \\ B_{GT}({}^3H) &= |M_{Gamow-Teller}|^2 = \frac{1}{2} | \langle He(1/2)^+ | \sum_n \tau_n^+ \sigma_n | {}^3H(1/2)^+ \rangle |^2; \end{aligned} \quad (25)$$

$F_0(Z+1, T_e)$ is the Fermi function [16], which takes into account the Coulomb distortion of the outgoing s-electron with the asymptotic kinetic energy T_e in the final nucleus with the charge

$Z + 1$. The matrix elements can be calculated analytically by angular momentum and isospin algebra. By integrating over the phase space one obtains:

$$\Gamma_{decay}^{\beta}(^3H) = \frac{1}{2\pi^3} m_e (G_F \cos(\vartheta_C) m_e^2)^2 [B_F(^3H) + B_{GT}(^3H)] \cdot I^{\beta}(^3H);$$

$$B_F(^3H) + B_{GT}(^3H) = 5.645; \quad I^{\beta}(^3H) = 2.88 \cdot 10^{-6}; \quad (26)$$

The half life is then given by:

$$Theory : \quad T_{1/2}^{\beta} = \frac{\ln 2}{\Gamma_{decay}^{\beta}(^3H)} = 12.32 \text{ years}; \quad Experiment : T_{1/2}^{\beta} = 12.33 \text{ years}; \quad (27)$$

The same reduced Fermi and GT transitions are needed for the determination of the induced relic neutrino capture reaction (1).

$$\Gamma_{capture}^{\beta}(^3H) = \frac{1}{\pi} (G_F \cos(\vartheta_C))^2 F_0(Z + 1, T_e) [B_F(^3H) + B_{GT}(^3H)] p_e T_e \cdot \frac{n_{\nu,e}}{\langle n_{\nu,e} \rangle}$$

$$= 4.2 \cdot 10^{-25} \frac{n_{\nu,e}}{\langle n_{\nu,e} \rangle} [\text{for 1 tritium atom/year}];$$

$$with : \quad \langle n_{\nu,e} \rangle = 56 \text{ cm}^{-3}; \quad (28)$$

The expression (28) gives the relic neutrino capture rate per year by only one tritium atom. It is proportional to the local overdensity $n_{\nu,e} / \langle n_{\nu,e} \rangle$ with to today's average relic neutrino density $\langle n_{\nu,e} \rangle \approx 56$ [electron-neutrinos / cm^3] for $T_0 = 1.95$ Kelvin in the universe.

The effective mass of the Tritium source of KATRIN corresponds to this part of the source activity, of which the decay electrons arrive without inelastic scattering (and energy loss) in the detector for counting. Different values are given in the literature for this effective mass. Kaboth et al. [17] give 66 *microgram*. In a previous publication [5] we assumed after consultation with the KATRIN collaboration 50 μg . Guido Drexlin [18] told us, after we finished this manuscript, that the correct value is 20 μg . Thus we modified our results for the effective mass to the value 20 μg . This means $2 \cdot 10^{18}$ *Tritium*₂ molecules. The capture rate of relic neutrinos is then:

$$\text{Capture rate at KATRIN: } N_{\nu}(KATRIN) = 1.7 \cdot 10^{-6} \cdot \frac{n_{\nu,e}}{\langle n_{\nu,e} \rangle}; \quad (29)$$

For the average relic neutrino number density $\langle n_{\nu,e} \rangle = 56 \text{ cm}^{-3}$ this corresponds to every 590 000 years a count. So the critical question is how much is the number density of the relic neutrinos increased by gravitational clustering in the solar system or better in our galaxy. Due to the small mass of the neutrinos one expects a large free streaming length and thus a clustering on the scale of galaxies and their halo of about 1 Mpc or even of galaxy clusters around 50 Mpc.

Ringwald and Wong [7] investigate the relic neutrino gravitational clustering as a byproduct of the clustering of dark matter. They start with density profiles of dark matter for different virial-masses (from 10^{11} to 10^{16} solar masses) of galaxies and calculate with the Vlasov equation trajectories of the relic neutrinos for different neutrino masses $m_{\nu} = 0.15 eV; \quad 0.3 eV; \quad 0.6 eV$. The relic neutrino number overdensities are shown in their [7] figure 3 and 4 and vary between the value 1 and 10^4 . Ref. [7] shows also, that the gravitational clustering of the neutrinos is possible on the scale of galaxies and their halos of about 1 Mpc.

Lazauskas, Vogel and Volpe [6] assume, that the neutrino overdensity is proportional to the baryon overdensity in galaxy clusters. (Average number baryon density in the universe:

$< n_b > = 0.22 \cdot 10^{-6} \text{ cm}^{-3}$.) They estimate a neutrino overdensity of $n_{\nu,e} = 10^3$ to 10^4 on the scale of 50 Mpc for galaxy clusters. If one assumes the result of Ringwald and Wong [7], that relic neutrinos can cluster on the scale of a single galaxy and their halo and uses the proportionality to the baryon overdensity of Lazauskas et al. [6], then one can expect very optimistically overdensities up to $n_{\nu,e}/< n_{\nu,e} > \leq 10^6$ in our neighbourhood. With this optimistic estimate of the upper limit for the relic neutrino overdensity of 10^6 one obtains from equation (29) :

$$N_{\nu}(KATRIN) = 1.7 \cdot 10^{-6} \cdot \frac{n_{\nu,e}}{< n_{\nu,e} >} [\text{year}^{-1}] \approx 1.7 [\text{counts per year}]; \quad (30)$$

This seems not possible to measure for the moment. One way out would be to increase the effective activity of the tritium source. An effective mass of 2 milligram Tritium would mean with the above optimistic estimate of the relic neutrino number overdensity $n_{\nu,e}/< n_{\nu,e} > \approx 10^6$ about 160 counts per year, which should be feasible.

Till now we did not include the finite energy resolution of the KATRIN spectrometer of $\Delta E \approx 0.93 \text{ eV}$ (see ref. [18]) and the background. With this resolution and the background one hopes to reduce the upper limit of the electron neutrino mass to about 0.2 eV (90% C.L.). fitting at the upper end of the Kurie plot at $Q - m_{\nu,e}$ the electron spectrum (21) to determine the Q-value and the neutrino mass. The electron peak due to the capture of the relic neutrinos lies at $Q + m_{\nu,e}$. The neutrino mass and the energy resolution and the background remains the same as for the determination of the neutrino mass. One has only one additional fit parameter more (or two, if one counts the width of this peak), the counts in the peak at $Q + m_{\nu,e}$. At least it should be possible to obtain an upper limit for these counts and by that to determine an upper limit of the local relic neutrino density $n_{\nu,e}$.

5. Conclusions.

The Cosmic Microwave Background (CMB) of photons allows to look back in our universe to about 300 000 years after the Big Bang (BB). Today's CMB has a temperature of $T_0 = 2.7255 \pm 0.0006 [\text{Kelvin}]$. The Cosmic Neutrino Background decoupled much earlier about 1 second after the BB and has today a temperature of $T_0 = 1.95 [\text{Kelvin}]$. Thus one can look back to about 1 second after the BB, if one is able to measure details of the cosmic (relic) neutrino background.

There are two major problems, which make the detection of the neutrino background very difficult and perhaps at least today impossible:

- With the average relic neutrino number density of $< n_{\nu,e} > = 56 \text{ cm}^{-3}$ KATRIN could measure only every 590 000 years a count. So the hope is with the local overdensity due to gravitational clustering of the neutrinos in our galaxy. Estimates for this overdensity $n_{\nu,e}/< n_{\nu,e} >$ vary widely from about 10^2 to 10^6 . With the optimistic estimate of a local overdensity of 10^6 one obtains with KATRIN 1.6 counts per year. If one could increase the effective mass of the tritium source from 20 microgram to 2 milligram, this optimistic estimate of the overdensity would mean 160 counts per year.
- The second problem could be the energy resolution of the KATRIN spectrometer of $\Delta E = 0.93 \text{ eV}$. With this resolution one expects to extract from the electron spectrum (21) at the upper end of the Kurie plot at $Q - m_{\nu,e}$ a very accurate Q-value of the order of milli-eV and an upper limit of the electron neutrino mass of about $m_{\nu,e} = 0.2 [\text{eV}]$ 90% C.L. with an energy resolution of 0.93 eV and a background. If one can fit the Q value and the electron neutrino mass accurately enough, the position of the electron peak from the

induced capture of the relic neutrinos is known to be at an electron energy of $Q + m_{\nu,e}$. The energy resolution and the background is the same at $Q - m_{\nu,e}$ and at $Q + m_{\nu,e}$. One should with KATRIN at least be able to determine an upper limit for the local relic neutrino density.

After we did send our manuscript to Guido Drexlin, he pointed out to us the related ref. [17] and a value of the effective mass of the KATRIN Tritium source of only $20 \mu g$, which is now used in this manuscript for estimating the counting rates [18].

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